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By

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THE BURNING MECHANISM OF AN ATOMIZED LIQUID FUEL IN A TURBULENT
STREAM

S. M. Kogarko and V. Ya. Basevich

(Moscow)

Various ideas have been expressed on the burning mechanism of an atomized liquid fuel. In some of these [1], it is assumed that, owing to the fine spray which is realized in industrial apparatus, the rate of droplet vaporization in the flame zone is so high that the duration of burning is determined only by the intermixing of the fuel vapor and oxidizer.

In an earlier work [2], it was discovered that in the flame zone, as the atomized fuel is burned up, the decrease in the amount of the liquid phase corresponds to the same increase in the combustion products, i.e., the burning mechanism is a diffusion mechanism relative to the fuel droplets. By disturbing this mechanism, there would be vaporization of part of the fuel in the flame zone, which would be accompanied by rapid burning, which would lead to fuel accumulation in some part of the zone. Inasmuch as we judged [2] the amount of vapor phase only by the difference between the amount of liquid phase and the combustion products, inaccuracies are possible in this determination. Therefore, it was advantageous to trace directly the con-

tent and consumption of the vapor phase.

In order to expose possible deviations from the diffusion mechanism, varied burning conditions were chosen for the study, including those under which this deviation might manifest itself: high velocities and accelerations of the stream, previous partial vaporization of the fuel, high initial temperatures, and the leanest possible mixtures, at which the probability of combustion is lowered [3].

In the present work an evaluation is made of the vapor concentration of an atomized liquid fuel in the flame zone and the mechanism of its decrease is studied.

Method. The principal diagram of the apparatus is shown in Fig. 1; its structure was described in more detail earlier [2,3]. The apparatus consists of a compressor, electric 1 and gas 7 (for obtaining temperatures over 300°) heaters and a pneumatic fuel atomizer 2, mounted either at a distance of 175 mm from the entrance to the combustion chamber 3, or at a considerably greater distance, when a homogeneous mixture is desired. There are two versions of the combustion chamber: 1) expanding from an entrance cross section of 40 x 40 mm to a cross section of 40 x 135 mm at a length of 400 mm and preserving this cross section of 40 x 40 mm. The difference in the construction of the chambers allowed a stream to be obtained either with a rate which varied little, or with acceleration along the length of the chamber. The side walls of the combustion chamber were made of quartz. By using hydrogen pilot burners 4, the two-dimensional tongue of the flame was stabilized. The pressure was atmospheric.

The vapor concentration in the flame zone was determined spectroscopically. Benzene, which has absorption bands in the short-wave region of the spectrum, was used as the fuel. The light source was

a carbon arc, fed by a low-voltage transformer. The entire width of the combustion chamber was illuminated (40 mm) at a light-beam diameter of 10 mm. The absorption spectrum was photographed for 15 to 20 seconds using an ISP-22 quartz spectrograph; the results were processed further using an MF-4 automatic microphotometer.

As is known, the absorption spectra of benzene vapor and liquid benzene differ from one another [4], so the vapor concentration may be recorded independently in the presence of liquid benzene.

In order to determine the vapor concentration of benzene, the intensity maxima of three lines in the absorption bands $\lambda = 2528.6$ and 2589.1 Å were recorded. The average vapor temperature was previously determined relative to the intensity maxima $\omega = 39,385$ and $39,220$ cm^{-1} to $\omega = 39,546$ cm^{-1} ($\lambda = 2528.6$ Å) and $\omega = 38,463$ and $38,298$ cm^{-1} to $\omega = 38,624$ cm^{-1} ($\lambda = 2589.1$ Å). The vapor concentration of the benzene was determined by graduated curves taken in a separate vessel in the required temperature range.

Thus it was possible to determine the average vapor concentration and vapor temperature of the benzene at various points in the combustion zone. The drawback of the method is the impossibility of recording their instantaneous values. The recording was carried out along the axis of the combustion chamber when the flame was stabilized in the form of a right cone.

A chemical analysis of the gases in the combustion chamber could be carried out in the apparatus. Determination of the local composition of the mixture was accomplished using a trap with liquid nitrogen.

The recording of the droplet dimensions by impressions on rods flying through the combustion chamber showed that the droplet diameter

was from 10 to 100 μ , at high supplies it was greater. In order to get the coarsest dispersion, the atomizing air was excluded, and the droplet dimensions reached 200 μ . The flow rates in the chamber were determined by photoscanning the flame through a slit along the axis of the chamber. In the experiments with homogenized mixtures, the gas rate was determined by the same method, for which small particles of magnesium were added to the stream. They shone brightly during combustion. In addition, the flow rates of the air, fuel, etc. were determined by the usual methods.

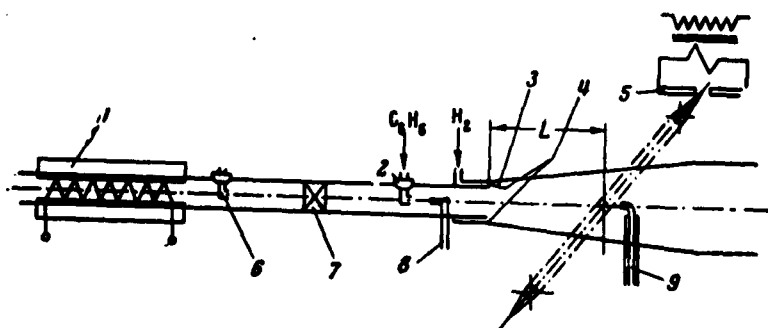


Fig. 1. Principal diagram of the apparatus: 1--electric heater, 2--pneumatic atomizer, 3--combustion chamber, 4--pilot burners, 5--arc, 6--place for installing atomizer, 7--gas heater, 8--thermocouple, 9--gas separator.

Results. The conditions for conducting the experiments with atomized fuel are shown in the Table, where t is the air temperature, V the flow rate at the entrance to the combustion chamber, α the local composition of the mixture, P the fuel-supply pressure, p_0 the partial pressure of the benzene vapor before the combustion zone.

In Experiment 1 (Fig. 2) fuel vaporization was recorded without combustion. Fig. 3 shows an example of the recording of combustion and besides the values of the vapor concentration and vapor temperature of the benzene, the values of the concentration of benzene and

oxygen relative to their values at the beginning of the combustion zone are given (p/p_0).

In the work with the expanding combustion chamber (Experiments 2 to 7), similar results were obtained at various temperatures, mixture compositions, atomizations, and flow rates. These data differ only in the fact that when the total composition of the mixture approaches stoichimetric, there is less discrepancy between the relative decrease in the vapors of the benzene and the oxygen. The vapor temperature did not exceed 120° .

Table

No. of experiment *	t, °C	V, m/sec	a	P, at	P _O , mm Hg	No. of experiment *	t, °C	V, m/sec	a	P, at	P _O , mm Hg
1	80	14.5	2.3	1.35	—	8	20	12.0	—	1.50	10.0
2	20	12.0	1.7	1.35	7.2	9	80	14.5	—	1.35	10.8
3	20	12.0	2.3	8.00	6.0	10	80	14.5	—	1.97	10.3
4	20	48.5	—	21.30	4.3	11	80	14.5	—	2.50	—
5	80	14.5	1.8	1.35	5.6	12	80	14.5	—	2.93	11.0
6	80	37.4	—	5.80	9.0	13	80	14.5	—	1.35	9.0
7	80	56.0	1.7	13.30	6.0	14	80	56.0	—	13.30	7.2
						15	320	96.0	—	5.85	9.5

*In experiments 1 and 8 through 15 the chamber was plane-parallel, in the others it was expanding.



Fig. 2. Vapor temperature and vapor pressure of benzene along the length of the chamber (Exp. 1).

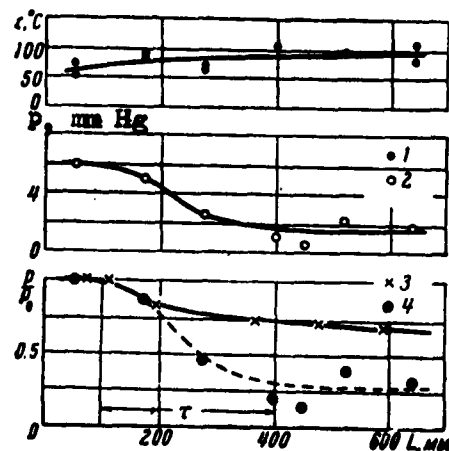


Fig. 3. Temperature (1), pressure of benzene vapor (2), relative concentration p/p_0 of oxygen (3) and benzene vapor (4) along the length L of the chamber; τ is the burning time of the benzene vapor (Exp. 7).

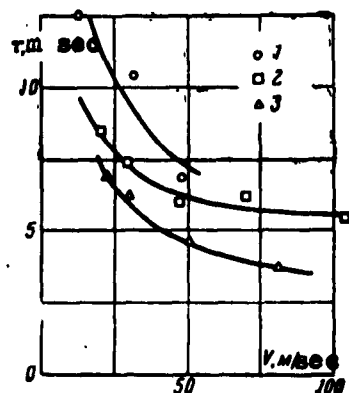


Fig. 4. Burning time τ of benzene vapor in the flame zone of atomized fuel (1) and of a homogeneous fuel-air mixture (2-- $\alpha = 1.25$ and 3-- $\alpha = 1.0$) at various flow rates V (Exps. 5, 6 and 7).

From these data one may approximately determine the time of rapid change in vapor concentration τ (burning time), using the known values of the gas velocity and distance between the cross sections of the combustion chamber which correspond to the beginning of the combustion zone and the point where the concentration is low and almost unchanged further (Fig. 3). Although this is an approximate evaluation, since

the beginning and end of this section are not accurately enough defined, it still allows a comparison to be made of the burning time of the vapors in a jet of atomized fuel with that in homogenous mixture of various composition (Fig. 4).

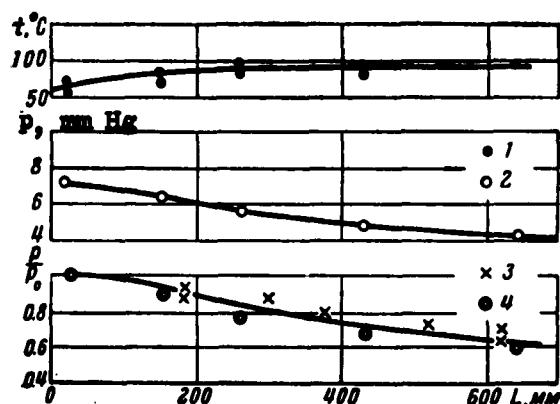


Fig. 5. Temperature (1), vapor pressure of benzene (2) and relative concentration p/p_0 of oxygen (3) and benzene vapor (4) along the length L of the chamber (Exp. 14).

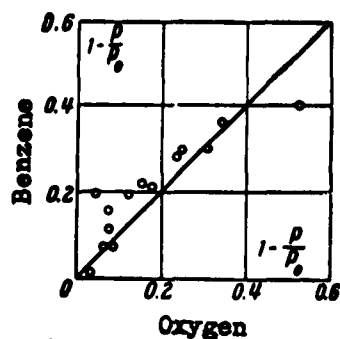


Fig. 6. Relationship between decrease $1 - p/p_0$ of benzene vapor and decrease in oxygen (Exps. 8, 9, 14).

Two types of recordings were obtained in the work with the plane-parallel combustion chamber (Exps. 8 to 14). The first of these repeated the recordings of Exps. 2 to 7 in nature. The second type (Exps. 8, 9 and 14) is illustrated in Fig. 5 and is characterized by the fact that the relative decrease in benzene vapor and oxygen has the same trend. Fig. 6 shows just this comparison of relative con-

centrations for the experiments indicated. Under those experimental conditions at which this type of recording could be clearly obtained, the vapor temperature did not exceed 95°.

It is possible to make recordings which are intermediate between these two types, if the total composition of the mixture a is changed (Fig. 7 a). If a small amount of city gas is mixed with the air, thereby simulating additional fuel vaporization before the flame zone, then recordings are obtained as are shown in Fig. 7 b. Close to a composition $\alpha = 1.5$ to 2, a sharp drop in the concentration of benzene vapor and oxygen is noticed. The value of this drop will be examined below.

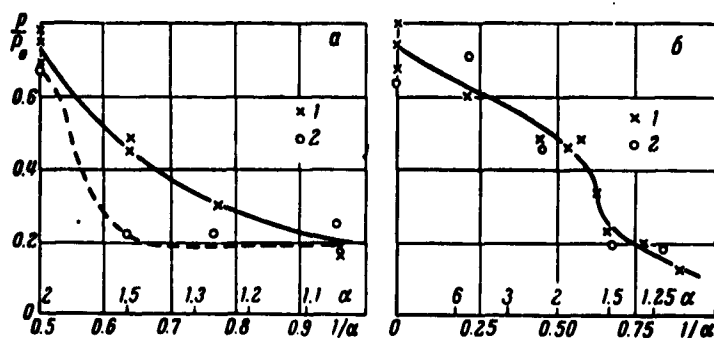


Fig. 7. Relative concentration p/p_0 of oxygen (1) and benzene vapor (2) at various total compositions of mixture (a--Exps. 9, 10, 11 and 12) and at various compositions of homogeneous gas-air mixture α (b--Exp. 9); $L = 350$ mm.

Discussion of the results. Under the same conditions at the input to the combustion chamber in both its configurations (plane-parallel and expanding), recordings of the two types described above may be obtained. This indicates a change in the structure of the burning zone and attests to the fact that chiefly recordings are made of fuel

vapor in the space between droplets, and not in the local burning zones near the droplets, where no serious change in the burning mechanism can be imagined.

The experiments in which was observed a rapid decrease in the relative concentration of benzene vapor with respect to the decrease in oxygen indicate the formation in the tongue of the flame of an independent zone of the combustion of previously vaporized fuel in the presence of the slower burning of droplets. This also supported by a comparison of the burning time of vapor in that zone with the burning time of homogeneous mixtures; it has the same order and in like manner varies with an increase in the flow rate. The burning time of vapors is somewhat higher, since it pertains to the leanest mixtures, $p_0 = 5.6$ to 9 mm Hg, or $\alpha = 2.3$ to 3.7 .

Under these conditions the vapor temperature of benzene in the flame zone could not substantially differ from the initial value, since the structure of this burning zone is apparently similar to the burning zone of homogeneous mixtures [2].

In the plane-parallel combustion chamber, the same previous vaporization of benzene held true in magnitude, as in the expanding chamber, but the hydrodynamics of the flow in this case apparently hindered the formation of an independent burning zone of fuel vapor in very lean (with respect to the vapor and liquid phases) mixtures. Therefore, it should be assumed that the case of coincidence of the rates of decrease of the relative concentration of vapor and oxygen corresponds to the absence of an independent zone of vapor burning. It is natural that with an enriching of the mixture, an independent zone of vapor burning must form, and actually does form, as is apparent from Fig. 7 a. In the experiments with an addition of city gas (not spectro-

scopically recorded), the sharp drop in the concentrations of fuel vapor and oxygen near $\alpha = 1.5$ to 2 (Fig. 7 b) also corresponds to the formation of an independent zone of vapor and gas burning.

The coincidence in the rates of decrease in the relative concentration of fuel vapor and oxygen corresponds to their joint diffusion to the burning zones near the burning droplets, since in a turbulent stream the transfer rate is not a function of the nature of the substance. However, it seems that in this case the vapor temperature must increase due to the diffusion of the combustion products in the fuel vapor. Indeed, there is no large increase in temperature.

In this case the low vapor temperature of the benzene is partially explained, probably, by the vaporization of the unignited droplets. Judging by previous experiments [3], these unburned droplets in the flame zone under similar conditions may be up to 5% (0.5 probability of combustion). It is to be remembered that the nonsteady-state propagation of a flame from a droplet during its ignition and propagation by superenriched zones also play a familiar role in this.

If some fuel which is difficult to vaporize could have been used instead of benzene and burning accomplished at richer total compositions, which correspond to higher average temperatures of the stream after burning, but a low previous vaporization, then, apparently, the fuel vapors could have been heated more along the length of the combustion chamber. However, a hydrocarbon which could give as strong absorption as benzene (and this is necessary for analysis at low vapor concentrations) and have a low vapor pressure could not be found. Toluene, o- and m-xylene and cumene were found to be unsuitable. Note that in the case of the burning of a previously vaporized fuel by joint diffusion of the vapor and oxygen to the droplet combustion zones, the total burning rate of the fuel may be expressed by the droplet

burning rate by the simple formula [5]

$$G = G_d \frac{\alpha_v}{\alpha_v - 1}$$

where G is the burning rate of the entire fuel, G_d the droplet burning rate and α_v the composition of the vapor-phase mixture.

Finally, in none of the recordings made did the rate of relative decrease in benzene vapor fall behind the rate of decrease in oxygen, including Exp. 15, where the stream temperature was increased to 320° in order to increase the absolute rate of vaporization and, in the first place, the mixture was impoverished almost to the limit, in the second place, the flow rate was increased to 98 m/sec and, in the third place, acceleration of flow was ensured due to the constancy of the chamber cross section, which lead to an increase in the relative velocities of the gases and droplets, in order to decrease the probability of droplet combustion.

Conclusions. In a range of initial temperatures of 20 to 320° , flow rates from 12 to 98 m/sec, and at various mixture compositions and droplet dimensions, the following is valid.

1. The burning mechanism is diffusional relative to the fuel droplets. No disturbances of this mechanism which would lead to vapor accumulation in the flame zone were discovered.

2. When fuel vapor forms before the flame zone, its burning can take place by joint diffusion with oxygen to the droplet burning zones, or with the formation of an independent vapor-burning zone (in some cases even at $p_0 = 4.2$ mm Hg.).

3. When burning lean mixtures, previous partial vaporization of fuel is not permissible only if it does not lead to the formation of an independent burning zone, since in this case the vaporized fuel

cannot be fully burned.

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